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Abstract
The ground based laser system for space debris cleaning will use powerful laser pulses, which can self-focused propagating through the atmosphere. We demonstrate that for relevant laser parameter the self-focusing can noticeably decrease the laser intensity on the target. We will show that the detrimental effect can be in great extent compensated by the optimal initial beam defocusing. The effect of laser elevation on the system performance will be discussed.

Key words: laser, self-focusing, space debris

Introduction
The proliferation of satellites in Earth orbit, increasing both in number and value, makes the problem of collision with orbital debris very real. One of the most practical solutions for the problem is debris removal with the help of a ground based pulsed laser. In this approach laser pulses ablate debris material, change the debris velocity and move the debris to a lower orbit where natural burn-up takes place. This method of debris removal was analyzed by the "Orion" project [1, 2] where requirements for the laser and optical and tracking systems were summarized. Two things have changed since completion of that project. First, the risk of valuable asset damage has increased and is now so serious that governments may be ready to spend money on orbital debris removal. Second, a significant advance in the powerful pulsed laser technology has taken place, mainly at Lawrence Livermore National Laboratory (LLNL), with completion of the National Ignition Facility (NIF) Project [3]. Systems designed for inertial confinement fusion applications are a near perfect fit for the orbital debris removal application.

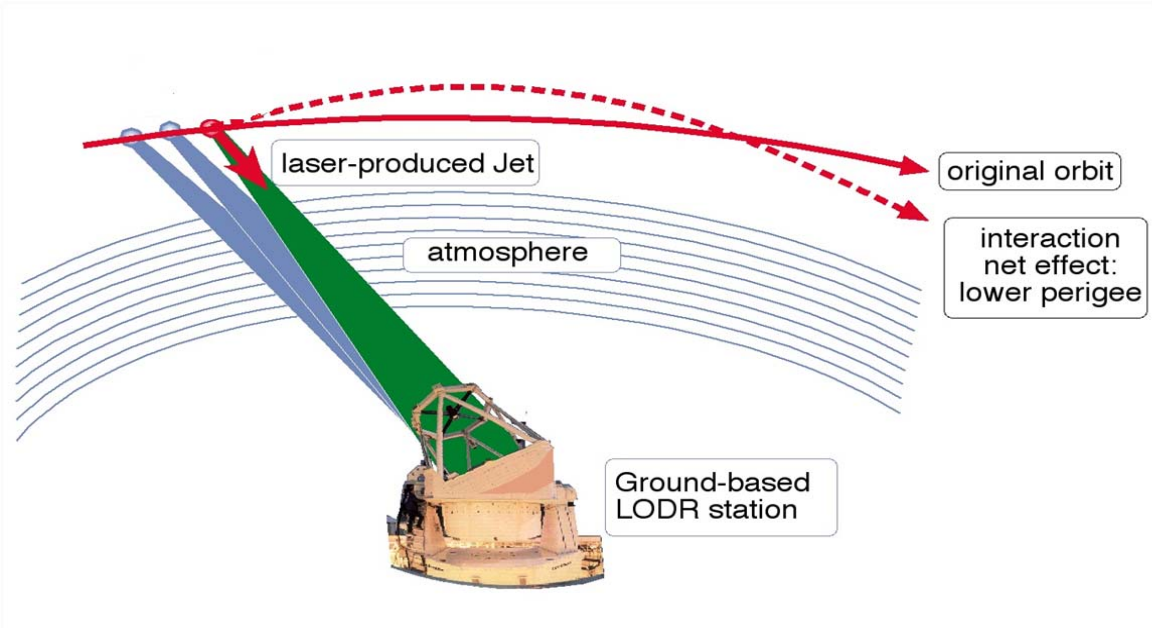

Fig.1. Schematic depiction of the laser space debris cleaning.

We start the analysis with requirements for the laser pulse on the target. Then we discuss beam propagation and focusing to more completely define requirements for the laser. Based on this we specify a range of parameters for laser operation. We demonstrate that the laser pulse power greatly exceeds the critical power for self-focusing in air. But because the laser light is propagated almost vertically, the self-focusing length is much longer than the thickness of the atmosphere. Our numerical calculations demonstrate that the spatial structure of the beam on the target is smooth, without filaments, but the nonlinear effects noticeably decrease the peak intensity. We demonstrate that the atmosphere can be treated as an additional focusing lens, and preliminary beam defocusing can significantly compensate for the detrimental effects of the atmosphere.

The detrimental effect of nonlinearity can be greatly reduced if the laser is placed at a high elevation. The reduction arises as the result of the decrease in the air density and the reduction of the atmosphere thickness through which the beam propagates.

In the last section we discuss the role of additional nonlinear effects, including the beam broadening caused by atmospheric turbulence. We demonstrate that these detrimental effects are important, but argue that proper optimization of the laser and beam control system renders the ground based laser space debris cleaning approach feasible.

1. Laser system requirements

In this section we will formulate the required parameters for the laser pulses following [4]. We start from the interaction of radiation with debris. High intensity pulsed laser radiation incident on debris vaporizes the surface material, creating recoil momentum that changes the debris velocity. It is clear that an optimal laser intensity exists for any specified pulse duration. At low intensity, the surface temperature and evaporation rate are low and the recoil momentum is small. At high intensity, a large fraction of the laser energy is used to create a plasma, which contributes little to the momentum change of the debris. A crucial parameter for pulsed laser debris removal is the coupling coefficient C_m, the ratio of momentum imparted to the target to the incident laser energy, $C_m = \Delta P / E$. A review of data illustrating the C_m dependence on intensity for different materials is presented by Phipps [2, 5]. The experimental data from different groups demonstrates that for broad ranges of wavelength, pulse duration, and pulse energy, the coupling coefficient maximum is reached at intensity

$$I_m = \frac{2.5}{\sqrt{\tau(ns)}} GW / cm^2, \tag{1.1}$$

where τ(ns) is the pulse duration in nanoseconds. This numerical coefficient is valid for Al alloys but does not change much for different materials and wavelengths. The temporal dependence indicates that the surface temperature and ablation is controlled by the thermal flux from the surface. As a function of laser intensity, C_m is peaked not far from the vaporization threshold, where plasma starts to be generated and absorptivity increases rapidly, which explains the weak sensitivity to target material. Typical values of C_m are 1-10 dyne/W [5]. Below I_m, the coupling coefficient drops sharply as intensity is reduced while above $I_{m\,,}$ the coupling coefficient gradually decreases. The fluency corresponding to optimal coupling is given by

$$F = 2.5 J / cm^2 \sqrt{\tau(ns)}. \tag{1.2}$$

We now derive the requirement for laser pulse energy that corresponds to delivering the optimal fluency to debris targets. The energy delivered by the laser to the vicinity of the target is required to be

$$E = \pi r^2 F, \tag{1.3}$$

where r is the radius of the beam in the target plane, and F is the fluency. An approximate expression for beam radius that accounts for beam quality and beam diffraction is

$$r = M^2 \frac{2\lambda L}{\pi D}, \tag{1.4}$$

where M^2 is a factor describing the beam quality in comparison to an ideal Gaussian beam, λ is the laser wavelength, L is the path length from the beam director to the target, and D is the diameter of the beam director. The effects of propagation through the atmosphere have thus far been ignored. The required laser pulse energy E for delivering the pulse fluency for optimal coupling is found by combining eqns. (3-5), which gives

$$\frac{ED^2}{\sqrt{\tau}} = \frac{10}{\pi} M^4 \left(L\lambda\right)^2 . \tag{1.5}$$

We now consider a specific example, in which $\lambda = 1\,\text{m}\mu$, $L = 1000\,\text{km}$, $D = 2\,m$ and $M^2 = 2$, the latter of which is a value that can be achieved for high-energy lasers by using spatial filters and adaptive optics systems. The path length $L = 1000\,\text{km}$ is chosen to represent the altitude where the most of debris are concentrated [2]. For this case, $r \approx 64\,cm$ and the required pulse energy is $E = 32\sqrt{\tau(ns)}$ kJ. For a solid state, NIF-like laser system with short pulse duration the output energy is limited by the nonlinear effects in the optical elements. For longer pulses, the energy is limited by saturation of the extracted energy. The optimal pulse duration for this type of laser is about 4 ns [4] and $E \approx 64\,kJ$.

For the above parameters the laser power is $16\,\text{TW}$, which is well above the critical power for self-focusing in air – $P_{cr} = 4.3\,\text{GW}$ for $1\,\text{m}\mu$ light. Even for the ideal beam quality $M^2 \approx 1$, the required power is over $1000\,P_{cr}$.The atmospheric turbulence and nonlinear effects can even further increase the required power. It is clear that the effect of nonlinearity on beam propagation must be considered.

2. Modeling nonlinear propagation

To avoid unnecessary complications, we first present the key concept using a simplified, though meaningful, model. The basic model reads:

$$i\frac{\partial \Psi}{\partial z'} + \frac{1}{2n_0 k_0}\Delta_{\perp}^{'}\Psi + k_0\, n_2(z)|\,\Psi\,|^2\,\Psi = 0.$$

Here, we consider a laser beam propagating vertically (compare to [6]). It is not very different from the optimal angle for the interaction with debris, which is ~ 30 degree from the vertical [4]. This simplification is not important, but will simplify the presentation.

It is customary to introduce dimensionless variables:

$\Psi(z',\vec{r}') = \sqrt{\frac{P_0}{r_0^2}} A(z,\vec{r})$, where dimensionless $z = z'/L_D$ and $\vec{r} = \vec{r}'/r_0$,

$L_D = 2n_0 k_0 r_0^2 = 4\pi\, n_0\, r_0^2 \,/\, \lambda_0, a$

$k_0 = 2\pi/\lambda_0$, $\lambda_0 = 1.06\ \ \mu\text{m}$, $k_0 = 5.93\ \ \mu\text{m}^{-1}$, $n_0 = 1.0$, $n_2\left(0\right) = 4.2\times10^{-19}\ \ \text{cm}^2/\text{W}$.

Here $z = 0$ corresponds to sea level. We assume the commonly used exponential density dependence with the atmosphere height -6 km $n\left(z\right)/n\left(0\right) = \exp\left(-z/Z_0\right)$, $Z_0 = 6\,km$. The nonlinear effects decay with height as

$n_2(z) = n_2(0) \cdot \exp(-z / Z_0)$. We use a normalization parameter r_0 to denote the initial radius of the beam (mirror radius), and normalize the power by $P_0 = \lambda_0^2 / (8\pi^2 n_0 n_2(0))$. Then we get

$$i\frac{\partial A}{\partial z} = -\Delta_\perp A - \exp(-z/h) |A|^2 A = \frac{\delta H}{\delta A^*}. \qquad (2.1)$$

Here $h = Z_0 / L_D$, $H = \int |\vec{\nabla}_\perp A|^2 \, dxdy - \frac{\exp[-z/h]}{2} \int |A|^4 \, dxdy$. For the parameters given above we get $L_D = 11855$ km, $P_0 = 0.339$ GW and $P_{cr} = 4\pi \cdot P_0 = 4.258$ GW for a Gaussian input beam. The equation has a Hamiltonian structure.

The problem is characterized by two dimensionless parameters P / P_{cr} and h, where typically $h \ll 1$. One more dimensionless parameter related to the beam focusing will be introduced later.

There are several important and well known relations for Eq. (2.1):

$$P = \int |A|^2 dxdy = const,$$

$$\frac{d^2}{dz^2} \int \vec{r}^{\,2} |A|^2 \, dxdy = 8H = 8 \int |\vec{\nabla}_\perp A|^2 \, dxdy - 4\exp[-z/h] \int |A|^4 \, dxdy. \qquad (2.2)$$

The relation (2.2) – ‘the Talanov theorem’ [7] is used to control numerical calculations. Usually the relation (2.2) is derived for uniform media, but it is valid for the inhomogeneous situation too.

Let us consider the propagation of the initially Gaussian beam. On the surface, at $z = 0$, we have

$$A(r, t, 0) = \sqrt{\frac{P_{in}}{\pi r_0^2}} \exp[-\frac{(1 + iC) r^2}{2 r_0^2}].$$

Here r_0 is the initial beam size, $C = k \cdot r_0^2 / F$ is the initial beam pre-focusing parameter (F has a meaning of a focal distance that in this case is a debris height L), and P_{in} is the input power of a laser beam. C is the third dimensionless parameter of our problem, defined as $C = L_D / Fa$. We solve the problem numerically for some specific parameters, but the situation with the same dimensional parameters will be equivalent. We solve numerically NLSE (2.1) in the domain $0 \le z \le z_m$, $0 \le r \le r_m$ with $z_m = F = 1000$ km and $r_m / r_0 = 10$. At r=0 we use a symmetrical boundary condition, and at $r = r_m$ the solution is set to $A = 0$ or is matched with the solution of the linear problem.

We would like to stress that the problem under consideration, though similar in terms of the basic equation to numerous self-focusing studies [8], is rather different in terms of physics. The considered laser beam has a much larger spot size – over 1 m. The self-focusing length of $L_{SF} \propto L_D / \sqrt{P / P_{cr} - 1}$ is much longer than the thickness of the atmosphere. This moves the self-focusing (collapse) point far beyond the atmosphere. In other words, we consider here the light propagation over a finite distance (the nonlinear layer of the finite thickness) and the collapse point is located beyond this region, where the propagation is linear. In this case the self-focusing effect compresses the beam but without catastrophic collapse of all the energy into a small volume. This is a well known nonlinear lens effect and here we can use it to relax the conditions on the size of the beam pre-focusing mirrors. The numerical modelling strongly indicates that for the problem treated here, even for input powers well above the critical power for self-focusing, the beam can maintain its integrity and is compressed as a whole.

The calculations were performed for r_0=1 m, L=1000 km, and one micron light. The parameter $C = C_{\max}$ for the optimal focusing in the linear case is 5.93. The distribution of the laser intensity in the focal plane for few different values of P / P_{cr} is presented in Fig.2.

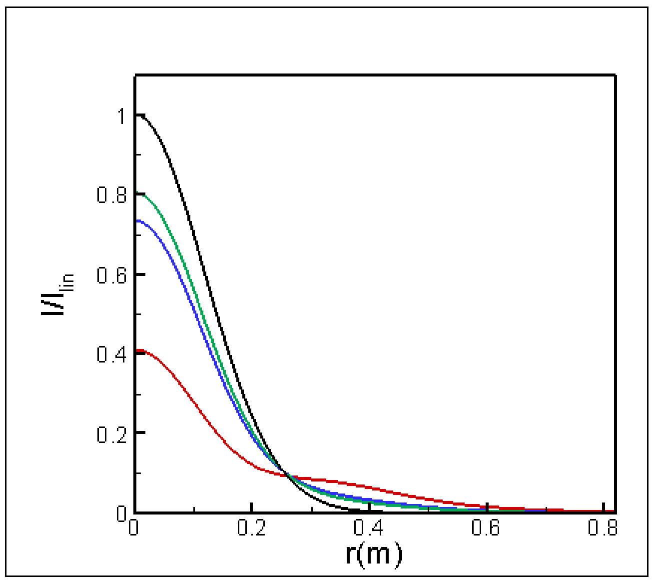

Fig.2. The intensities are normalized to the peak intensity of the linear case for the focal point $z = F = 1000\ km$.
Red line: $P_{in} / P_{cr} = 1500$ Blue lines: solid – $P_{in} / P_{cr} = 900$.
Green line – $P_{in} / P_{cr} = 760$. Black line – linear case.

The intensities are normalized to the peak intensity for the linear case. One can see the noticeable decrease in peak intensity for high P / P_{cr}. The effect increases with increases of power; I/I_{lin} is 0.8 for P / P_{cr} =760, 0.734 for P / P_{cr} =900, and 0.41 for P / P_{cr} =1500. The main reason for the decrease is that the nonlinear lens results in the focusing of radiation before the focal point of the linear problem. In Fig. 3 we plot the intensity of the beam centre as a function of z, with P / P_{cr}=1500, and we see that it peaks before the focal point $z = 1000$ km.

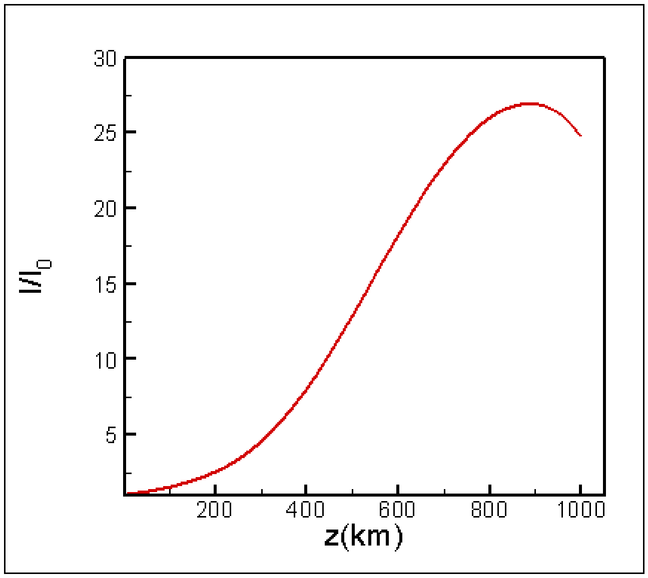

Fig.3. The intensity in the beam centre as function of z for $P_{in} / P_{cr} = 1500$
The intensity is normalized to the initial peak intensity at the point of laser position.

It is natural to try to compensate the nonlinear effects by preliminary beam defocusing, in our case by decreasing C. The results are presented in Fig. 4. We see that the proper initial defocusing can noticeably compensate the detrimental effect of nonlinearity.

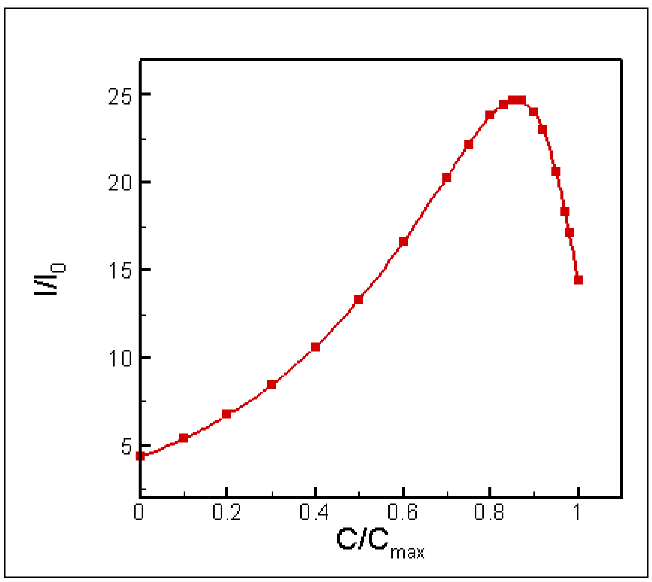

Fig. 4. Intensity, as a function of the ratio $C / C_{\max}$, where $C_{\max} = 5{,}93$.
Here $r_0 = 1$ m, $P_{in} = 1500\ P_{cr}$ and $z = 1000$ km.

The radial distribution of the beam intensity in the focal plane is presented in Fig. 5.

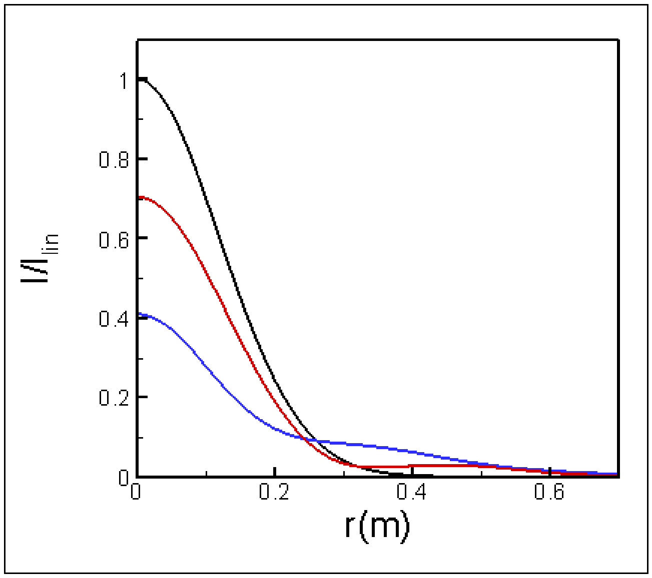

Fig. 5. Intensity vs. r at different chirp parameters. Black line – linear case, blue line – C=5.93, and the red line corresponds to the optimal C=5.51. Here $r_0 = 1$ m, $P_{in} = 1500\ P_{cr}$ and $z = 1000$ km.

We see that for the optimal defocusing the peak intensity drops only 0.7 times in comparison with non-compensated drop to 0.4, and the effect of self-focusing can be compensated to a great extent.

Now, let us discuss the effect of the laser elevation. The nonlinear refractive index is proportional to the density of air, so placing the laser at a high elevation is a natural way to reduce the detrimental nonlinear effects and the effects of propagation. We have already discussed the three dimensionless parameters used to characterize the problem – P/P_{cr}, L_D/L, and L_D/Z_0. From equation (2.1) one can see that positioning the laser at the height h is equivalent to a decrease $n_2 \exp(-h/Z_0)$ times or an increase of $P_{cr} \exp(h/Z_0)$ times.

The height of the laser is small compared to the propagation distance L, and the change in L_D/L can be disregarded. As a result, a change in the laser altitude is equivalent to a change in P/P_{cr} only. To take an example, the positioning of the laser at a height of 3 km reduces P/P_{cr} to 0.6 times that at sea level. At 4 km (the height of Mauna Kea), reduces 0.51 times. Direct numerical modeling confirms these arguments; the change in the laser height is completely equivalent to a reduction in P/P_{cr}.

The laser elevation is an equivalent to the reduction of laser power for the sea level laser. Therefore, the results presented in Fig. 2 can be interpreted as an intensity distribution in the focal plane for a laser power P/P_{cr}=1500 and laser elevations of 0, 3, and 4 km. We see that laser elevation helps to decrease the magnitude of the intensity reduction at the target. In the same way the initial defocusing will help to compensate the drop.

Let us discuss qualitatively the self-focusing dependence on parameters. Consider the atmosphere as a nonlinear layer with the thickness Z_0=6 km. The beam modulation resulting from nonlinear effects is characterized by the B integral [8, 9], the nonlinear phase shift between the central and outer parts of the beam with radius a after propagation through the layer. The B=1 or phase difference 2π is considered as a boundary when the nonlinear effects becomes important. It is convenient to write the B integral in terms of laser power

$$B = n_2 I(kZ_0) = 2\frac{P}{P_{cr}}\frac{kZ_0}{(ka)^2} = 4\frac{P}{P_{cr}}\frac{Z_0}{L_D}.$$

For the above parameters and $P/P_{cr} = 1500$ the B integral ~3 and nonlinear effects are important. Laser elevation decreases $B \propto \exp(h/Z_0)$ and reduces the nonlinear effects.

Up to now all calculations were done for a fixed value of $L_D/L = 10$. Below, we present some calculations for longer diffraction length, mirror radius $r_0 = 2\ m$. The B integral drops $\sim 1/r_0^2$ and the role of nonlinear effects drops rapidly. The radial distribution of intensity at the focal point is less effected by the self-focusing. The peak intensity for P/Pcr=1500 is decreased 2.44 times for linear focusing conditions and only 1.42 times for the optimal chirp.

The further increase in power eventually results in filamentation and fast beam degradation. The filamentation starts with axi-symmetric mode [10] and our treatment is adequate for the initial stage of the process [10]. The beam destruction with power increases is demonstrated on Fig.5. We see strong drop in peak intensity after P/P_{cr} >2000 with formation of a ring filament which is impossible to correct in simple way. It means that for reasonable focusing of laser pulse we must keep the B integral below 3-4.

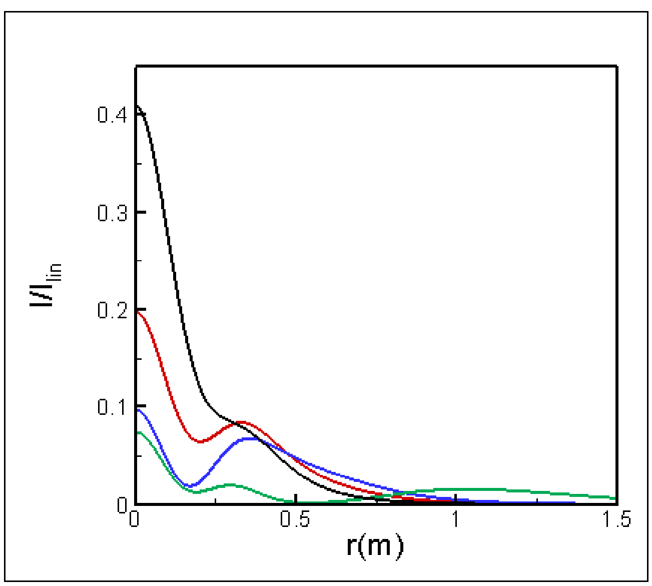

Fig. 6 Radial intensity profile in focal point for the high laser power.
Black line – $P/P_{cr}=1500$, red line – $P/P_{cr}=2000$,
blue line – $P/P_{cr}=2500$, green line – $P/P_{cr}=5000$. Here r_0=1m

The our results demonstrate that the intensity distribution for situations without filamentation looks close to Gaussian. In Fig. 6 we present the phase at different heights as functions of r^2. We see that the phase changes, but with good accuracy it is proportional to r^2, meaning that despite the nonlinear effects, locally, the beam structure is close to a Gaussian one shape with beam size *a* and chirp *C* changing during the propagation

$$A(r,z)=\sqrt{\frac{P}{\pi a(z)^2}}\exp[-\frac{(1+iC(z))r^2}{2a^2(z)}] \ . \qquad (2.3)$$

This fact provides us with the opportunity to introduce a simplified description of self-focusing, Using relation (2.2) one can get ordinary differential equations for a(z) and C(z). Analysis demonstrates that on the long propagation from the atmosphere to the focal point even the small deviation from the Gaussian shape are important and the simplified description should be carefully adjusted to account for this. The situation is different when laser pulse propagates from the orbit to the ground [11], when phase front aberration in atmosphere has no propagation distance to be developed and propagation is less sensitive to atmospheric propagation effects

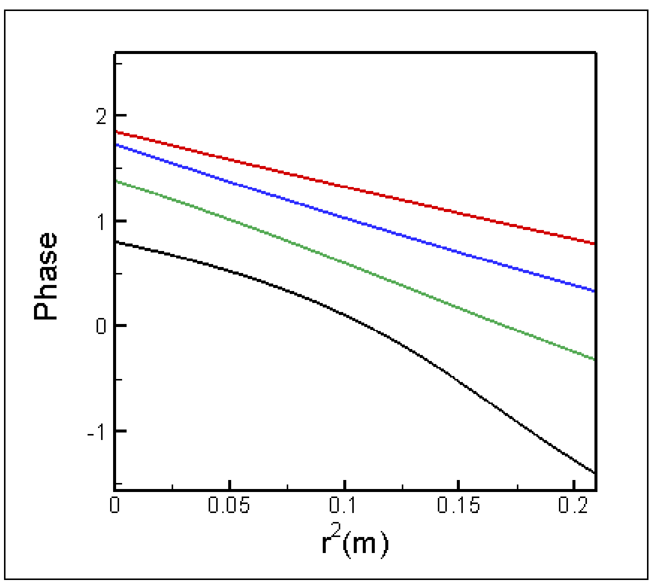

Fig. 7 Phase versus r^2 at different heights. Red line corresponds the height 100 km,
blue – 300 km, green – 500 km, black – 700 km.
Here $C=5{,}51$, $r_0=1$ m and $P_{in}/P_{cr}=1500$ and $z_*=3\,km$.

3. Processes affecting beam propagation

Turbulent broadening

Turbulence in the atmosphere scatters the light and produces broadening of the propagated beam. The scattering is induced by density and temperature perturbations, resulting in fluctuations of the refractive index. Let us estimate the effect of turbulence on the focusing of laser radiation.

Atmospheric turbulence is usually treated as isotropic and uniform, with the Kolmogorov spectrum of turbulence. In this situation the correlation function for the refractive index $n(r)$ fluctuations satisfy the relation

$$<\left(n\left(r_1+r\right)-n\left(r_1\right)\right)^2>=C_n^2 r^{2/3}.$$

The turbulence is characterized by the constant C_n^2. The typical values of C_n^2 are in the range of 10^{-13} -10^{-15} $1/m^{2/3}$ near the ground, and decrease with height.

The most common semi-empirical model describing the beam broadening by turbulence in the linear approximation uses the following expression for the beam radius on the target r_t:

$$r_t^2 = r_{cl}^2 + r_{tur}^2,$$

where

$$r_{cl} = \frac{2\lambda L}{\pi D}$$

is the diffraction limited spot radius, L is the debris orbit height, D is the focusing mirror diameter. In practical situations this value often must be increased by the beam quality factor.

For turbulent broadening we use the Dowling/Breaux model [12], based on both theoretical studies and experiment. The most important parameter in the model is the Fried coherence length r_0

$$r_0 = 1.7\left[\left(\frac{2\pi}{\lambda}\right)^2 \int_0^z C_n^2 \left(1-\frac{s}{L}\right)^{5/3} ds\right]^{-3/5}. \qquad (4.1)$$

In our case of a thin atmosphere this can be re-written as

$$r_0 = 1.7\left[\left(\frac{2\pi}{\lambda}\right)^2 \int_0^z C_n^2 dz\right]^{-3/5}.$$

In terms of r_0 the spot radius at the target can be represented as [12]

$$\frac{r_t}{r_{cl}} = \left[1+0.18\left(\frac{D}{r_0}\right)^2\right]^{1/2}.$$

In the expression (4.1) the focusing mirror is placed at $z=0$ and the focal plane is at $z=L$. The multiplier $\left(1-s/L\right)$ in (4.1) means that scattering near the focus is less important than scattering near the mirror; the ray scattered near the mirror deviates from the beam axis even for free propagation, whereas the ray scattered near the focal spot has no time to deviate. This effect is unimportant in our case.

To make progress, we need a model of atmospheric turbulence. A simple model that is used frequently assumes that the turbulence is maximal near the surface and, starting from the height $z = z_0 = 10\ \mathrm{m}$, drops as $1/z$. Consider the height dependence as

$$C_n^2 = C_n^2 \frac{z_0}{z + z_0}.$$

This model is applicable up to an altitude $\sim 3\ \mathrm{km}$; beyond that, the more complicated model, with an exponential decline of C_n, i.e., the Hafnagel model [12] must be used. For simplicity, we set C_n to zero at the height $h = 6\ \mathrm{km}$. For low turbulence levels ($C_n^2 = 10^{-15} m^{-2/3}$) the Fried coherence length will be about $1\ \mathrm{m}$, and even for a $2\ \mathrm{m}$ diameter mirror, turbulence can be a problem, broadening the beam. The turbulence problem can be greatly reduced by placing the laser on a high mountain, but even in this case it can be a problem for a large diameter mirror.

The important nonlinear process, which can affect the powerful beam propagation, is stimulated Raman scattering. The dominant Raman process is rotational Raman scattering by nitrogen (SRRS) [13, 14]. In the atmosphere pressure broadening dominates up to the height L ~40 km, and the gain coefficient is independent of density and does not change substantially [13, 14]

$$G \approx 2{,}5 \cdot 10^{-6}\ \mathrm{cm/MW}.$$

The total gain for Raman scattering to grow from the noise level to a level high enough to destroy the beam is gIL~20. From here we find that the SRRS is appreciable for intensities $2\mathrm{MW/cm}^2$.

The above estimate assumes stationary SRRS. For pulses shorter than the Raman relaxation time, SRRS is in a non-stationary regime and the process threshold is increased [13, 14]. The relaxation time changes from 0.1 nsec on the ground to 10 nsec at 40 km. The threshold intensity is about 10 MW/cm^2 for a 1 nsec pulse and ~100 MW/cm^2 for 0.1 nsec. We see that, using the shorter pulses, we can suppress Raman scattering.

The laser elevation only slightly reduces the amplification length (about 10% for h~4km), but increases in the relaxation time can greatly increase the Raman threshold.

We must mention that the above estimates for the effects of Raman scattering are conservative. The threshold calculation [14] assumes that 1% of the radiation is converted to scattered light. Raman scattering is peaked in the forward direction, and energy losses are minimal. Even the noticeable scattering may not change the target irradiation.

We see that the suppression of the various detrimental effects implies contradictory requirements. To suppress Raman scattering we need to increase the director diameter (to reduce the intensity). But this enhances the beam broadening by atmospheric turbulence. The shortening of the pulse to suppress Raman scattering decreases the laser system efficiency and increases the self-focusing. The design of a laser system for debris clearing must optimize both the physics and engineering requirements. But one thing is clear: a laser elevation ~ 4 km will greatly improve the system performance.

Conclusions

We demonstrated that for a ground based laser space debris cleaning system the self-focusing can greatly affect the beam propagation. Owing to the finite thickness of the atmosphere the self-focusing does not filament the beam but changes only its macroscopic parameters – focal length and beam size. We showed that the initial beam defocusing can, to a large extent, compensate the detrimental effect of nonlinearity.

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